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Prioritization and Optimization of Pavement Preservation Treatments

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Prioritization and Optimization of Pavement Preservation Treatments

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Abstract:	This report describes a framework for the selection of pavement preservation treatments which can best utilize an available pavement preservation budget. It includes formulation of project-specific strategies, evaluation of funding requirements, and setting of priorities. The technology is illustrated using data for 75 sections from Stratford District. The key component of this framework is an Action Plan which recommends preferred and fall-back pavement preservation strategies for all individual pavement management sections. The task of preparing Action Plans is assigned to experienced regional staff. The Action Plan documents the existing pavement condition, integrates all major pavement maintenance and rehabilitation efforts into a unified preservation plan, and co-ordinates pavement preservation functions of different offices within the Ontario Ministry of Transportation. The allocation of pavement investments, in a manner that yields the maximum benefit to the total pavement network, was achieved by linear programming. The linear programming solution considers all section-specific strategies listed in the Action Plans. Sensitivity analyses evaluated the effect on the linear programming solution of using different optimization goals and different budget constraints. While the objective function used maximizes only technical benefits of pavement investments, it can be modified to include societal benefits also.
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1/ Introduction

The pavement management process can be roughly divided into three related phases:

a) a data gathering phase concerned with collecting and storing data required to make pavement preservation decisions;

b) a decision phase where pavement inventory data are used to make recommendations regarding pavement preservation actions; and

c) a feedback phase which evaluates consequences of pavement investments.

This report is mainly concerned with the second phase. Its objective is to describe the methodology for recommending pavement preservation actions developed for the Ontario Ministry of Transportation Pavement Management System. This methodology consists of the following steps:

1. Development of a preferred pavement preservation strategy, and alternative fall-back strategies, for every pavement management section.

2. Aggregation of funding requirements for individual pavement sections and their evaluation on district, regional, or provincial levels.

3. Selection of pavement preservation strategies which would best utilize the available budget.

Step 1 represents project level evaluation, while Steps 2 and 3 represent network level evaluation and prioritization. The application of the methodology is illustrated using recent data obtained for Stratford District.

Any methodology for recommending pavement preservation actions depends on the amount and quality of inventory data. For this reason, the current method of gathering and storing pavement inventory data is briefly described.

2/ Data Required for Pavement Preservation Decisions

To facilitate planning of pavement rehabilitation actions, the Ministry of Transportation has been systematically rating pavement deterioration since the mid-1960s. The original rating scheme was based on a subjectively assigned Pavement Condition Rating [1]. It was realized in the 1970s that the evaluation of pavement deterioration should be done using a more objective and consistent measure. This led to the development and recent introduction of the Pavement Condition Index (PCI) [2].

The PCI is measured on a scale of 0 to 100. Newly-constructed pavements have a PCI of about 95, and rehabilitation is usually done when PCI is between 60 and 40. PCI comprises two different physical parameters:

a) the riding quality of the pavement surface measured by a response-type pavement roughness meter, and

b) the extent and severity of 15 pavement surface distresses evaluated against well-defined measurement scales.

The two parameters are combined using a mathematical formula.

Together with the development of the PCI, new procedures for pavement sectioning, data collection, and storage and retrieval were developed to update and improve the existing pavement management processes.

The basic pavement management unit is a pavement management section. The pavement management sections have relatively uniform pavement structure and traffic loadings, and exhibit relatively uniform pavement deterioration. The typical length of pavement management sections is approximately 10 km.

The pavement condition surveys used to determine the PCI are done every two years and all data obtained during these surveys are stored as historical records in a pavement management data base. These include roughness data, the severity and density of 15 pavement surface distresses, and PCI. The data base operates under the FOCUS data base management system [3], and contains data for approximately 2000 pavement sections representing nearly all King's highways with asphalt concrete surfaces.

The data base was designed to store and retrieve all basic data necessary for planning specific pavement preservation treatments for individual sections. In addition to pavement performance data, each pavement section is also characterized by its functional class, geometric data, traffic volumes, and data describing pavement structural composition, and past maintenance and rehabilitation treatments.

Examples of data which can be readily retrieved from the pavement management data base are shown in Tables 1 and 2. Table 1 shows an example of a Pavement Performance Record which summarizes past pavement deterioration data. The Pavement Performance Records are available for all sections in the data base. In this case, data are for a section from Stratford District.

Table 2 shows an Action Plan Fact Sheet for the same section. The Action Plan Fact Sheet consists of two parts. The first part summarizes pavement inventory data such as pavement structural data, functional class, and past performance. The second part lists two key estimates:

a) The expected change in PCI during the next 3 years, ΔPCI_3. This estimate (ΔPCI_3) provides a systematic measure of the expected rate of pavement deterioration. It is based on the assumption that no preservation action, other than routine maintenance, will be taken during the 3-year period. ΔPCI_3 is used for the section-specific pavement deterioration prediction to estimate when the pavement performance will reach the minimum acceptable level and when a pavement preservation action will be needed.

b) The Action Plan, which lists all pavement preservation actions planned within a 5-year planning period.

The Action Plan of the Action Plan Fact Sheet is prepared for all sections. It is the key pavement management tool which documents the existing pavement condition, **integrates** all major pavement maintenance and rehabilitation efforts into a unified preservation plan, and **co-ordinates** pavement preservation functions of different offices within the Ministry (e.g., District maintenance, Regional rehabilitation and Head Office policy and funding functions).

3/ Project Level Prioritization

The tasks of predicting the expected rate of pavement deterioration (ΔPCI_3) and recommending pavement preservation strategies required for Action Plans are assigned to experienced regional staff. Regional staff are in constant contact with the portion of the highway network over which they have responsibility, and can fully exercise their engineering judgement and knowledge of local conditions. They also work closely with District staff, who are in charge of pavement maintenance, to co-ordinate and plan pavement maintenance. To help the regional staff, detailed guidelines describing how to approach these tasks have been prepared [4]. Salient features of the guidelines for recommending pavement preservation strategies are briefly described below.

The guidelines provide a structured procedure on how to identify, for each section:

a) a preferred pavement preservation strategy, and

b) its alternative, fall-back (or contingency) strategies.

The preferred pavement preservation strategy is defined as the strategy which addresses in the most cost-effective way the problem of keeping the pavement in an adequate state of pavement preservation. It encompasses both major maintenance treatments (e.g., patching) and rehabilitation treatments (e.g., overlays), taken singly or in combination with each other. The preferred strategy must take into account existing resources and procedures and is usually based on life-cycle economic analysis. The preferred strategies are usually recommended for implementation before the pavement reaches a minimum acceptable serviceability level.

The fall-back strategies provide recommendations of what to do if a postponement or rescheduling of expenditures associated with the preferred strategy is required. It is realized that, compared with the preferred strategy, all fall-back strategies would result in lower pavement performance and/or higher construction costs.

The fall-back strategies should provide "substantial" alternatives to the preferred strategy. Small variations in the preferred strategy, such as a change in overlay thickness by 20% or a postponement of the overlay by only one year, do not usually constitute substantial alternatives.

In order to facilitate the development of fall-back strategies which:

a) are practical strategies providing a substantial postponement of expenditures,

b) enable a systematic assessment of consequences of not implementing the recommended preferred strategies on time, and

c) enable the making of comparisons of these consequences among different sections,

the fall-back strategies are developed using a structured format as **holding** strategies and **deferred** strategies.

A **holding** strategy is designed to hold the pavement for at least 2 or 3 years until the preferred strategy can be undertaken. For example, according to the Action Plan given in Table 2, the preferred strategy calls for a 90 mm overlay in 1989. The corresponding holding strategy recommends patching in 1988 and the same 90 mm overlay in 1991. The patching component of the holding strategy is intended to hold the pavement until 1991 and to postpone the major part of the expenditure from 1989 to 1991.

A **deferred** strategy assumes that it is necessary to defer all expenditures associated with the preferred strategy by at least 3 years if the preferred strategy is a rehabilitation treatment. If the preferred strategy recommends only a maintenance treatment, the deferral may be just 1 or 2 years. Returning to the example in Table 2, the deferred strategy assumes that no funds (other than those for routine maintenance) are available until 1992 and, based on this constraint, recommends the deferred strategy of padding and resurfacing in 1982. The deferred strategy should address the new situation in the most cost-effective manner. The expected pavement performance curves for all strategies listed in Table 2 are shown in Figure 1.

By default, all sections also have do-nothing strategies which assume that no pavement preservation expenditures (other than those for routine maintenance) will be made during the 5-year planning period. The consequences of do-nothing strategies can be judged by the ΔPCI_3 estimates.

It should be noted that not all sections require the full palette of preservation strategies for the 5-year planning period. For example:

a) many sections may not require any specific preservation treatment other than routine maintenance, which is not included on the action plans;

b) some preferred strategies, particularly those scheduled for the beginning of the planning period, may be already approved and may not require any fall-back strategies; and

c) for some sections, no feasible holding strategies may exist.

In summary, the preferred, holding and deferred strategies have the following common features:

1. They are section-specific pavement preservation strategies reflecting local conditions which combine and co-ordinate all major maintenance and rehabilitation treatments.

2. They can contain any type of treatment. The only restriction is that the treatment be substantial (i.e., costs exceed approximately $3000 per section per year) and is usually planned at least one year in advance.

3. Each strategy must be fully described using the parameters listed in Table 2. These include type of treatment ("DESCRIPTION" in Table 2), its timing ("PROGRAM YEAR"), and its consequences ("PCI AFTER" -- PCI predicted immediately after the treatment is applied; and "LIFE YEARS" -- predicted life-span of the treatment in years). Predictions of "ΔPCI_3", "PCI AFTER", and "LIFE YEARS" are based mainly on engineering judgement exercised by experienced regional staff familiar with local conditions. This situation is necessitated by the unavailability or poor documentation of the many models required for performance prediction of various pavement preservation treatments.

4/ Evaluation of Funding Requirements

The costs of all pavement preservation strategies can be summarized from individual action plans to obtain the total funding requirements for a district, region or the province and compared with available budgets. This process is illustrated using data for Stratford District which has 134 pavement management sections comprising about 1100 km of 2-lane highways. Of the 134 sections, 75 sections required some pavement preservation funding during the 5-year planning period. It must be emphasized that all data used in this report are provided for illustration only (any other interpretation of the data is incorrect).

Table 3 lists Action Plan strategies, in terms of their cost and timing, for the first 10 sections requiring funding in Stratford District. (Also shown in Table 3 are the results of linear programming which will be discussed later.) The funding requirements for all sections in Stratford District are summarized in Table 4. Table 4, as well as Tables 5 and 6, were obtained by retrieving data from the FOCUS-operated data base. The distribution of costs required to fund the preferred, holding, and deferred strategies is plotted in Figures 2a to 2c. It may be noted that the total cost of the preferred strategies ($26.73 million in Table 4) is not evenly distributed during the planning period. Also, $7.69 million worth of the preferred strategies do not have any fall-back strategies.

Tables 5 and 6 show the cost consequences of postponing preferred strategies for Stratford District by utilizing corresponding holding and deferred strategies, respectively. For example, the total cost of the preferred strategies which can be postponed by utilizing their corresponding holding strategies is $16.19 million (Table 5). The total cost of these holding strategies is $19.90 million, or about $3.7 million higher. However, while the bulk of the funding requirements for the preferred strategies occurs in 1989 ($7.36 million in Table 5), the highest funding requirement for the corresponding holding strategies ($5.46 million) is postponed to 1991.

5/ Setting Priorities

In general, there are two types of techniques underlying all prioritization methods—ranking techniques and optimization techniques. Both techniques may be acceptable methods for establishing priorities, and each has advantages and disadvantages. Usually, ranking techniques are thought to be simple, while optimization techniques are considered complex and comprehensive. The basic philosophical difference between them is that ranking techniques establish priorities by considering individual actions (e.g., preservation treatments) one at a time, whereas optimization techniques consider all actions at the same time and try to select that combination of actions which would optimize the overall result.

A considerable number of ranking schemes can be developed to prioritize pavement preservation investments. The ranking, or an orderly arrangement of candidate projects, can be done by using:

a) a single decision criterion or a priority indicator, such as benefit/cost ratio, or PCI level; or

b) a combination criterion which combines a number of priority indicators into one number (e.g., traffic volume and composition, PCI level, ΔPCI_3, pavement structural adequacy, and Freezing Index).

Available funds are allocated first to projects with the highest ranking. Projects which cannot be funded during the first year are transferred to the second year and ranked again together with the projects planned for the second year. The same procedure is repeated in subsequent years.

6/ Optimization on Network Level

From the viewpoint of individual sections, the aggregated cost of all preferred strategies constitutes the most effective overall funding level. If this funding level exceeds the available yearly budget, either during one or more specific years of the planning period, or during the entire planning period, not all preferred strategies can be implemented as recommended. Some of the preferred strategies must be replaced by holding, deferred, or do-nothing alternatives. Because there are usually multiple investment objectives and many sections involved, the selection of investment alternatives which would best utilize the available budget is a difficult problem.

Any practical solution of this problem must take into account technical as well as societal investment objectives. For example, a technical investment objective may be to obtain the highest possible pavement performance, while a societal investment objective may be to achieve an equitable distribution of construction jobs in the province. An ideal situation occurs when the selected investment alternatives fully satisfy both technical and societal objectives.

6.1/ Linear Programming

Given a limited budget, the selection of investment strategies can be optimized using linear programming. A linear programming (LP) technique can maximize (or minimize) an aggregate consequence of individual actions (i.e., an objective function) given a set of limitations or constraints. In other words, preservation dollars can be allocated in a manner that yields the maximum benefit to the given pavement network [5]. The LP problem was formulated as follows.

Maximize expression:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} X_{ij}\, B_{ij} \qquad (1)$$

Subject to:

$$\sum_{i=1}^{n} X_{ij} <= 1 \qquad \text{for } j = 1 \text{ to } n \qquad (2)$$

and

$$\sum_{i=1}^{n}\sum_{j=1}^{m} X_{ij}\ C_{ijt} <= B_t \qquad \text{for t = each year within the planning period} \tag{3}$$

where:

B_{ij} = benefit associated with implementing strategy i for section j
X_{ij} = a decision variable. For mixed integer programming model, $X_{ij} = 1$ if strategy i is selected, and 0 otherwise.
C_{ijt} = cost of strategy i for section j in year t.
n = number of strategies for a given section (maximum was four; preferred, holding, deferred, and do-nothing).
m = number of sections requiring funding during the 5 year period (75 for Stratford District)
B_t = budget available in year t.

Equation 1 is called the objective function and represents the sum of benefits which can be obtained from implementing all selected strategies. The goal is to maximize the value of the objective function subject to the constraints (Equations 2 and 3). Equation 2 ensures that only one strategy "unit" is selected per section. Equation 3 requires that available yearly budgets are not exceeded. The investment alternatives considered by LP are the strategies listed on Action Plan Fact Sheets. They are practical feasible alternatives with systematically evaluated costs and consequences.

Because there is no single "right way" how to measure benefits from pavement investments, the measurement and evaluation of benefits which determine the LP solution must be carefully considered. In order to explore different ways of measuring pavement investment benefits and the consequences of using different benefits on the LP solution, the benefits were measured in four different ways and the resulting LP solutions were obtained and compared. The following objective functions, utilizing non-monetary benefits, were evaluated.

6.1.1/ Objective Function 1

The benefits used to calculate the value of Objective Function 1 (B_1) were expressed as the time in years the pavement performance will be above the acceptable level (y), multiplied by the section length (L).

$$B_1 = \sum_{i=1}^{n}\sum_{j=1}^{m} y_{ij}\ L_j \tag{4}$$

For example, considering data given in Table 2 (Action Plan Fact Sheet) and in Figure 1, the benefit of the preferred strategy is the product of 14 years (the strategy is expected to last from 1989 to 2003) and the length of 2.4 km. The benefit of the do-nothing alternative for the same section was calculated as the ratio of the section's ΔPCI_3 (6 PCI units in Table 2) and the average

ΔPCI_3 for all sections in Stratford District (6.3), multiplied by 5 (years). Given a limited budget, this formulation maximizes the number of sections with an acceptable level of pavement performance.

6.1.2/ Objective Function 2

The benefits used to calculate the value of Objective Function 2 (B_2) were similar to those of Objective Function 1 but were also factored to include the influence of traffic.

$$B_2 = \sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij} L_j T_j \qquad (5)$$

$$T_j = \log (\text{AADT of cars} + 3\ \text{AADT of trucks}) \qquad (6)$$

AADT = Annual Average Daily Traffic

This formulation increases benefits for sections with high traffic volumes, particularly truck volumes. According to Equation 6, truck volumes were multiplied by 3 because user savings attributed to the improved pavement performance have been estimated to be roughly three times greater for trucks than for cars. This estimate is based on data given in Reference 6.

6.1.3/ Objective Function 3

The benefits used for Objective Function 3 were expressed as a benefit/cost ratio. The benefits were those of Objective Function 2, and the costs were the estimated strategy costs given on the Action Plan Fact Sheets. No penalty was included for do-nothing alternatives.

6.1.4/ Objective Function 4

Objective Function 4 (B_4) attempts to maximize user benefits by using the area underneath the performance curve (PCI - time curves in Figure 1) rather than the length of the expected life-span used for Objective Functions 1, 2 and 3.

$$B_4 = \sum_{i=1}^{n} \sum_{j=1}^{m} A_{ij} L_j T_j \qquad (7)$$

where:

A_{ij} = area under performance curve of strategy i for section j and,
L_j and T_j were defined before.

For simplicity, all pavement performance curves used to calculate B_4 were assumed to be straight lines, even though the performance curves for individual pavement sections in Ontario can also show an increasing or decreasing rate of pavement deterioration with time [7]. The linear rate is a

compromise, and there is also some evidence from the AASHO Road Test that the rate of pavement deterioration due to traffic loadings is linear when results are plotted against a roughness dominated measure such as the PCI [8]. It may also be noted that the performance curves in Ontario established for groups of similar pavements are approximately linear [9].

The objective functions evaluated in this report were based only on technical considerations. While the LP model can optimize the value of one objective function only, it is possible to construct a single objective function which would incorporate both technical and societal objectives in a single expression. For example, the technically calculated benefits, such as Objective Function 4, may be adjusted according to the geographical area in which they occur. The important point to remember is that the funds which can be saved by using optimization instead of ranking are substantial, and should always be considered seriously [10].

The linear programming solution was obtained by LP83/MIP83 microcomputer software [11], which can provide both real number linear programming (RNLP) and mixed integer linear programming (MILP) solutions. MILP solution ensures that X_{ij} of Equation 1 are either 1 or 0. RNLP solution allows X_{ij} to be real numbers which may result in "split" strategy solutions. For example, a split strategy solution may recommend implementing 20% of the preferred strategy and 80% of the do-nothing strategy (Table 3, Section 1, Column 13).

The differences between RNLP and MILP solutions were evaluated for the 75 sections in Stratford District using Objective Function 1. The computation time required for MILP solution using IBM-AT microcomputer was about 24 hours while the corresponding time for RNLP solution was only 5 minutes. However, despite the large difference in the computation time, the solutions were quite similar in terms of the total benefits (7493.6 versus 7520.2 according to Table 7) and in terms of the strategies selected for individual pavement sections. In fact, the strategies selected for the first 10 sections were identical (Table 3, Columns 5 and 6). The number of split strategy solutions allowed by RNLP (five, Table 5) represents only 7% of the 75 sections. Furthermore, it can be shown that the number of split strategy solutions cannot exceed the number of constraints defined by Equation 3 (that is, the number of years in the planning period). Thus, for larger problems, such as those involving sections from several districts, the percentage of split strategy solutions will be even lower. After considering the computation time savings and the intended use of the LP solution as a management decision support tool only, all subsequent analysis used only real number linear programming.

6.2/ Sensitivity Analysis of the Objective Function

The example results of a sensitivity analysis for the four objective functions done for data from Stratford District are listed for the first 10 sections in Table 3, Columns 5 to 9. The overall results are summarized in Table 7. The analysis assumed a yearly budget of $5 million for 7 consecutive years. The total yearly cost of the preferred strategies during this period reached a maximum of $10.8 million in 1989 (Table 4 and Figure 2a).

The linear programming solution equalizes and limits the total yearly cost of the selected strategies to be below the $5 million constraint. This was done by selecting the fall-back strategies (holding, deferred, and do-nothing strategies), instead of the preferred strategies, for some sections, while maximizing the total benefit. The composition of the resulting LP solutions for Objective Functions 1 to 4 is given in Table 7. The composition for Objective Function 4 is also illustrated in Figure 2d. It may be noted that no do-nothing alternatives were selected for the relatively high yearly budget of $5 million.

The results of sensitivity analyses given in Tables 3 and 7 indicate that the linear programming solution is sensitive to the formulation of the objective function. For example, the LP solution for

Objective Function 2 recommends implementation of holding strategies on 32 pavement sections, while the solution for Objective Function 4 recommends holding strategies for only 20 sections. Objective Function 2 maximizes the total length of pavement sections above the minimum acceptable PCI level. Because holding strategies usually include patching, and patching can keep pavement performance just above the minimum acceptable level at relatively low cost, many holding strategies were selected for Objective Function 2. Objective Function 4 takes into account that the benefit to the road users varies with the level of PCI above the minimum acceptable level. Therefore, holding strategies with their patching and low pavement serviceability become less attractive. These results underline the need for careful and clear identification of pavement investment objectives, i.e., an unequivocal declaration of what the investments are supposed to achieve.

6.3/ Sensitivity Analysis of the Yearly Budget Constraints

A sensitivity analysis on the effect of changing the yearly budget constraints was done by reducing the yearly budget of $5 million to $1 million in four equal steps. The analysis was done (for data from Stratford District) using Objective Function 4 only. The purpose was to determine the effect of budget reduction on the strategy selection and on the value of the objective function.

Initially, as the budget was reduced, fall-back strategies were chosen, which allowed for the deferral of expenditures to latter years (Table 8). With further budget reductions, the budgets did not permit any expenditures on the increasing number of sections, which resulted in the increasing number of do-nothing recommendations.

The do-nothing strategies, like other alternatives, were also selected to maximize the total investment benefits. The do-nothing strategies were characterized by negative benefits (disbenefits) since they allowed the PCI to drop below the minimum acceptable level (Figure 1). The LP solution selected the do-nothing strategies for those sections where the drop below the minimum acceptable level had the smallest disbenefits.

With the reduction in the yearly budgets, the value of the corresponding objective function summarizing the total investment benefits was also reduced. Figure 3 shows that this relationship was not linear. As the budget was reduced, the LP solution first eliminated those strategies which provided the lowest benefits. A similar picture emerges from a plot of an average benefit/cost ratio versus yearly budget given in Figure 4. The average benefit/cost ratio for the yearly budget of $1 million was about 2, while the corresponding ratio for the yearly budget of $6 million dropped to 1.5. With the increasing budget constraints, the LP solution retains only the most cost-effective strategies which results in an increase of the average benefit/cost ratio.

7/ Funding Decisions and Their Consequences

The Action Plan strategies clearly identify the most cost-effective funding requirements for individual pavement sections as well as consequences of not providing the required funding on time. These project-level strategies are determined by those responsible for pavement design and who are familiar with local conditions.

On the network level, the funding requirements for individual sections can be summarized and prioritized to provide authoritative overall funding recommendations. For a given budget, the selection of specific sections (and treatments) to be funded can be also optimized by linear

programming. Consequences of any restrictive funding decisions can be readily identified in terms of section-specific consequences.

Table 9 lists recommended strategies for the first 10 sections of Stratford District assuming a $4 million yearly budget and Objective Function 4. This is an example of an optimized pavement preservation plan which can be used as a basis or starting point to consider prior commitments and other constraints during the formulation of the actual pavement preservation program.

Pavement management is also concerned with overall long-term funding requirements to maintain the health of the pavement network above a predetermined, acceptable level. Because cost and life-span estimates are known for all candidate strategies, it is relatively easy to predict the overall health of the network during the 5-year planning period for different funding levels.

8/ Conclusions and Recommendations

1. The prioritization framework described in this report reflects the distributive nature of the decision-making process involved in pavement maintenance and rehabilitation planning and programming in the Ministry. The Ministry is divided into five Regions and 18 Districts served by experienced staff, and concerns and inputs of the field staff are accommodated within the framework. Also, funding and planning decisions made on the network level can be easily translated into project-specific actions and consequences.

2. Action Plans prepared for individual pavement sections provide sufficient information for prioritizing and optimizing pavement preservation strategies on both project and network levels, and enable one to estimate the overall health of the network at the end of the planning period.

3. The aggregate cost of all preferred strategies, obtained for individual pavement sections by life-cycle economic analysis, constitutes the most effective overall funding level.

4. Linear programming is a very useful management tool which can help to allocate pavement investments in a manner that yields the maximum benefit to the entire pavement network. The funds which can be saved using optimization instead of ranking are substantial, and should always be considered seriously.

5. The way in which pavement investment benefits are measured must be carefully considered. Ideally, the benefits should reflect both technical and societal investment objectives. For addressing technical investment objectives, Objective Function 4, which takes into account benefits to the road user, is recommended.

6. For a full-scale application of linear programming within the Ministry's pavement management framework, the procedure for calculation of strategy benefits should be automated using the FOCUS programming environment.

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References

1. Chong, G.J., Phang, W.A., and Wrong, G.A., "Manual for Condition Rating of Flexible Pavements - Distress Manifestations," Ontario Ministry of Transportation and Communications, Downsview, Ontario, August, 1975.

2. Hajek, J.J., Phang, W.A., Wrong, G.A., Prakash, A., and Stott, G.M., "Pavement Condition Index (PCI) for Flexible Pavements," Report Number PAV-86-02, Ontario Ministry of Transportation and Communications, Downsview, Ontario, August, 1986.

3. Information Builders Inc., "FOCUS Users Manual, Release 4.5," 1250 Broadway, New York, N.Y., 1001, 1983.

4. Pavement Management Study Group, "Outline of Concepts for Preparation of PMS Action Plans," Ontario Ministry of Transportation and Communications, Downsview, Ontario, September, 1986.

5. Kher, R.K., and Cook, W.D., "PARS - The MTC Model for Program and Financial Planning in Pavement Rehabilitation," Proceedings of North American Pavement Management Conference, Toronto, Ontario, March, 1985, pp. 6.23 to 6.40.

6. Transport Canada, Highway Branch, "Highway User Benefit Assessment Model HUBAM," 1986.

7. Hajek, J.J., Phang, W.A., Prakash, A., and Wrong, G.A., "Performance Prediction for Pavement Management," Proceedings, North American Pavement Management Conference, Toronto, Ontario, March, 1985, pp. 4.122 to 4.134.

8. Ullidtz, P., Simonsen, P., and Lentz, G., "The Analytical-Empirical Method Used in a Pavement Management System," Proceedings, 6th International Conference on Structural Design of Asphalt Pavements, The University of Michigan, Ann Arbor, 1987, pp. 795-806.

9. Bacchus, A, Cook, W.D., and Kher, R., "Development of Pavement Performance Curves: PCR/AGE Curve Analysis", PARS Report #2, Ontario Ministry of Transportation and Communications, Downsview, Ontario, March, 1979.

10. Lytton, R.L., "Optimization Methodologies," Proceedings, North American Pavement Management Conference, Toronto, Ontario, March, 1985, p. 6.3.

11. Sunset Software, "LP83 and MIP83 - A Professional Linear Programming System," 1613 Chelsea Road, San Marino, California, 91108, 1985.

Table 1/ Pavement Performance Record, Section 22, Stratford District

PAVEMENT PERFORMANCE RECORD

DISTRICT: 3
HIGHWAY :8

LHRS	OFFSET	LENGTH	DIRECTION	FACILITY	CLASS	LANES	AADT	TRUCK %
15870	2.90	2.4	B	A	C	4	32600	10.8

FROM: FREEPORT DR.

TO : FAIRWAY RD. INTERCHANGE

OVERALL PAVEMENT PERFORMANCE HISTORY

YEAR	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
AGE	16					21	22	23										
PCR	80					68	68	68										
PCI	78					71	66		66									
RCR	7.0					7.0	5.9	7.0	5.7									
DMI	22.8					40.0	40.0	38.5	38.5									

DETAILED PAVEMENT PERFORMANCE HISTORY

SEV.=SEVERITY, DEN.=DENSITY

		1978		1983		1984		1985		1986		19		19	
		SEV.	DEN.	SEV.	DEN.	SEV.	DEN.	SEV.	DEN.	SEV.	DEN.	SEV.	DEN.	SEV.	DEN.
C. AGG. LOSS & RAV.															
FLUSHING															
RIPPLING AND SHOVING															
WHEEL TRACK RUTTING		2	5	3	5	3	5	3	5						
DISTORTION				3	2	3	2	3	1						
LONGITUDINAL (WHEEL TRACK)	SING. & MULT. ALLIGATOR	2	2	2	4	2	4	2	4						
CENTRE LINE	SING. & MULT. ALLIGATOR	2	1	3	2	3	2	3	2						
PAVEMENT EDGE	SING. & MULT. ALLIGATOR			2	2	2	2	2	2						
TRANSVERSE	HALF,FULL & MULT. ALLIGATOR	2	5	2	5	2	5	2	5						
HEADER AND MIDLANE				2	1	2	1	2	1						
RANDOM															

SEVERITY OF DISTRESS CODES

1. VERY SLIGHT
2. SLIGHT
3. MODERATE
4. SEVERE
5. VERY SEVERE

DENSITY (EXTENT) CODES

1. <10%
2. 10-20
3. 20-50
4. 50-80
5. 80-100

MAJOR MAINTENANCE HISTORY

YEAR>	1986		
ITEM	I	II	III
TYPE(CODE)			
EXTENT %	0	0	0
COST	.0	.0	.0

SHOULDER CONDITION FOR GRAVEL SHOULDERS

YEAR>	1986	
	SEV.	DEN.

DISTRESS COMMENTS:

OTHER COMMENTS :

EXTENT OF MAINTENANCE TREATMENT IN 1986 (CODE)

	PAVEMENT	SHOULDER
MANUAL PATCHING	0	0
MACHINE PATCHING	0	0
SPRAY PATCHING	0	
ROUT & SEAL CRACKS	0	0
CHIP SEAL	0	0

DATE: AUGUST 26, 1987

Table 2/ Action Plan Fact Sheet, Section 22, Stratford District

ACTION PLAN FACT SHEET

DISTRICT: 3
HIGHWAY : 8

LINK	OFFSET	LENGTH	DIRECTION	FACILITY	CLASS	LANES	AADT	TRUCK %
15070	2.90	2.4	B	A	C	4	32600	10.8

FROM: FREEPORT DR.
TO : FAIRWAY RD. INTERCHANGE

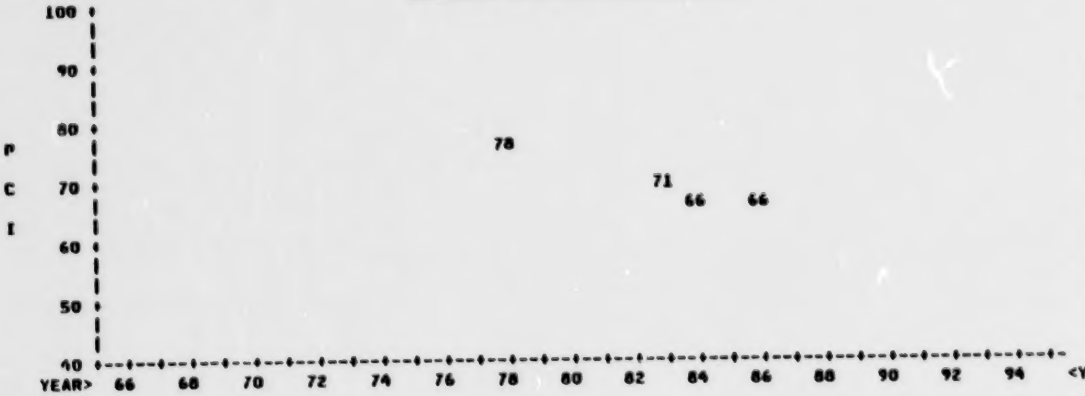
REHABILITATIONS

STRUCTURE	1	2	3	4	5
CONTRACT NO.					
SURFACE TYPE (CODE)					
TOTAL SURFACE THICKNESS, MM					
ADDED OVERLAY THICKNESS, MM					
MILL / REMOVE THICKNESS, MM					
BASE TYPE (CODE)					
BASE THICKNESS, MM					

SUBBASE TYPE (CODE) :
SUBBASE THICKNESS, MM :
SUBGRADE TYPE (CODE) : 2

STRUCTURAL COMMENTS:
SECTION LIMITS MAY BE CHANGED.

HISTORY OF PAVEMENT PERFORMANCE



URBAN SECTION, % : 0
PAVEMENT WIDTH,M : 14.6
SHOULDER TYPE : 0
LOAD RESTRICTION :
YEAR OF LAST SKID TEST :
OTHER DEFICIENCIES :

PAVEMENT CONDITION:	YEAR	PCI	RCR	DMI
	1986	66	5.7	38.5

ESTIMATED CHANGE IN PCI AFTER 3 YEARS > 6 <

PREFERRED, HOLDING AND DEFERRED STRATEGIES

	PART	DESCRIPTION	CODE	PROG YEAR	EXTENT %	COST/KM ($1000)	PCI AFTER	LIFE YEARS	S
PREFERRED STRATEGY	I	90MM HOT MIX RESURFACING	HM90	89	100	140	95	14	
	II								
HOLDING STRATEGY	I	MACHINE PATCHING (MAINLY E.B.L.)-25%	MP	88	25	30	66	14	
	II	90MM HOT MIX RESURFACING	HM90	91	100	140	95		
DEFERRED STRATEGY	I	90MM HOT MIX RESURFACING, 35-40% PADDING	HM90PAD40	92	100	200	95	14	
	II								

STRATEGY COMMENTS:

PREPARED BY:
DATE: AUGUST 26, 1987

Table 3/ Detailed Results of Linear Programming

Section Number	Strategy	Total Cost in $1000's	Year	Decision Variable, Xij [a]								
				Objective Function Used (yearly budget $5,000,000)					Yearly Budget Constraint Using Objective Function 4 (in $1000's)			
				1 Int.	1 Real	2	3	4	4000	3000	2000	1000
1	2	3	4	5	6	7	8	9	10	11	12	13
1	Preferred Holding Deferred Do-Nothing	367 464	89 92	1	1	1	1	1	1	1	1	0.2 0.8
2	Preferred Holding Deferred Do-Nothing	237 392 459	90 88/92 93	1	1	1	1	0.2 0.8	1	1	1	1
3	Preferred Holding Deferred Do-Nothing	43 211	88 93	1	1	1	1	1	1	1	1	1
4	Preferred Holding Deferred Do-Nothing	273 383	89 89/92	1	1	1	1	1	1	1	1	1
5	Preferred Holding Deferred Do-Nothing	273 383	89 89/92	1	1	1	1	1	1	1	1	1
6	Preferred Holding Deferred Do-Nothing	830 910 978	89 88/91 93	1	1	1	1	1	1	1	1	1
7	Preferred Holding Deferred Do-Nothing	345 440 690	88 88/90 92	1	1	1	1	0.9 0.1	1	1	1	1
8	Preferred Holding Deferred Do-Nothing	269	92	1	1	1	1	1	1	1	1	1
9	Preferred Holding Deferred Do-Nothing	160 201 275	89 89/92 93	1	1	1	1	1	1	1	1	1
10	Preferred Holding Deferred Do-Nothing	391 491 671	89 89/92 93	1	1	1	1	1	1	1	1	1

a) Xij are defined by Equation 3. Zero values are not listed.
"1" means that the strategy will be done in its entirety."

Table 4/ Summary of Funding Requirements for Stratford District

STRATFORD DISTRICT IN 1000'S DOLLARS

STRATEGY TYPE	STRATEGY YEAR 1987	1988	1989	1990	1991	1992	1993	1994	TOTAL
ALL PREFERRED STRATEGIES		5458	10767	5914	1330	3147		114	26730
PREFERRED STRATEGIES LACKING FALL-BACK STRATEGIES		2820	2190	526	830	1210		114	7690
PREFERRED STRATEGIES HAVING FALL-BACK STRATEGIES		2638	8577	5387	500	1937			19039
ALL PREFERRED STRATEGIES HAVING HOLDING STRATEGIES		1533	7359	4861	500	1937			16190
ALL HOLDING STRATEGIES	462	1931	647	3702	5457	5307	305	2090	19901
ALL PREFERRED STRATEGIES HAVING DEFERRED STRATEGIES		2638	6153	4333					13124
ALL DEFERRED STRATEGIES		57				6131	11908	1783	19879

Table 5/ Consequences of Utilizing Holding Instead of Preferred Strategies

STRATFORD DISTRICT IN 1000'S. DOLLARS

STRATEGY TYPE	STRATEGY YEAR 1987	1988	1989	1990	1991	1992	1993	1994	TOTAL
ALL PREFERRED STRATEGIES HAVING HOLDING STRATEGIES		1533	7359	4861	500	1937			16190
ASSOCIATED HOLDING STRATEGIES									
1987		95	367						462
1988		252	587	1044		48			1931
1989			420	100	127				647
1990		1007	1349	1004		342			3702
1991		526	4418	480	33				5457
1992			1640	3667					5307
1993					305				305
1994					153	1937			2090
TOTAL									19901

Table 6/ Consequences of Utilizing Deferred Instead of Preferred Strategies

STRATFORD DISTRICT IN 1000'S DOLLARS

STRATEGY TYPE	STRATEGY YEAR 1987	1988	1989	1990	1991	1992	1993	1994	TOTAL
ALL PREFERRED STRATEGIES HAVING DEFERRED STRATEGIES		2638	6153	4333					13124
ASSOCIATED DEFERRED STRATEGIES									
1987									
1988			57						57
1989									
1990									
1991									
1992		3277	2854						6131
1993		977	6076	4855					11908
1994				1783					1783
TOTAL									19879

Table 7 - Evaluation of Objective Functions for Yearly Budget of $5 Million

Evaluation Parameter			Type of Objective Function				
			1		2	3	4
			Solution Type				
			Integer	Real	Real	Real	Real
Total Benefits			7493.6 a)	7520.2 a)	N/A b)	N.A	N/A
Strategy	Preferred	Cost c)	12357.0	13324.8	13470.3	16015.0	15134.2
		Number	39	38	38	51	45
	Holding	Cost	15013.0	14322.3	14111.2	10581.6	8784.9
		Number	30	31	32	21	20
	Deferred	Cost	2633.0	2356.0	2329.2	1071.4	6110.0
		Number	6	6	5	2	10
	Do Nothing	Number	0	0	0	1	0
Total		Cost	30003.0	30003.1	29910.7	27668.0	30029.1
		Number	75	75	75	75	75
Number of Split Strategy Solutions			0	5	5	4	4

* NOTES: a) Non-monetary Benefits
b) Not Applicable for Comparison
c) Costs are in $1000's

Table 8 - Evaluation of Yearly Budget Constraint

Evaluation Parameter			Yearly Budget (in $1000's)				
			5000	4000	3000	2000	1000
Total Benefits			503.0	475.3	399.5	292.4	147.4
Strategy	Preferred	Cost	15134.2	11810.8	9264.2	7435.7	3828.1
		Number	45	32	24	23	14
	Holding	Cost	8784.9	7915.1	5555.1	3013.2	1840.5
		Number	20	18	10	5	3
	Deferred	Cost	6110.0	9501.9	8510.0	5667.5	1982.8
		Number	10	18	16	10	3
	Do Nothing	Number	0	7	25	37	55
Total		Cost	30029.1	29227.8	23329.3	16116.4	7651.4
		Number	75	75	75	75	75
Number of Split Strategy Solutions			4	5	4	6	6

Table 9 - Example of an Optimized Pavement Preservation Plan

Section Number	Section Identification					Recommended Strategy			
	Hwy	LHRS	Offset (km)	Length	Dir.	Type	Description	Year	Cost x1000
1	4	12880	5.6	10.8	B	Preferred	Mill 35 mm," Padding 10 % & H.M. 50 mm (R)	1989	$367
2	4	12890	1.9	8.2	B	Preferred	Mill 35 mm & H.M. 50 mm (R)	1990	$237
3	4	12900	1.9	7.3	B	Deferred	Mill 25 mm, Padding 5 % & H.M. 50 mm (R)	1993	$211
4	6	13605	0	3.7	N	Preferred	Padding & H.M. 50+40 mm	1989	$273
5	6	13605	0	3.7	S	Holding	1. Mill 40 mm & H.M. 40 mm 2 Padding & H.M. 80 mm	1989 1992	$110 $273
6	6	13620	0.8	13.4	B	Holding	1 Patching 10% 2 Mill 25 mm Padding 10% & H.M. 90 mm (R)	1988 1991	$80 $830
7	6	13640	2.1	11.9	B	Holding	1. Patching 15 2. Mill 30 mm & H.M. 50 mm R	1987 1990	$95 $345
8	6	13650	2.4	9.3	B	Preferred	Mill 30 mm & H.M. 30 mm R	1992	$269
9	7	14500	6.8	2.3	B	Holding	1 . Patching 30 % 2. H.M. 90 mm	1989 1992	$41 $160
10	7	14510	1.1	5.6	B	Holding	1. Patching 30 % 2. H.M. 90 mm	1989 1992	$100 $391

* **NOTE:** (R) means Recycled Hot Mix

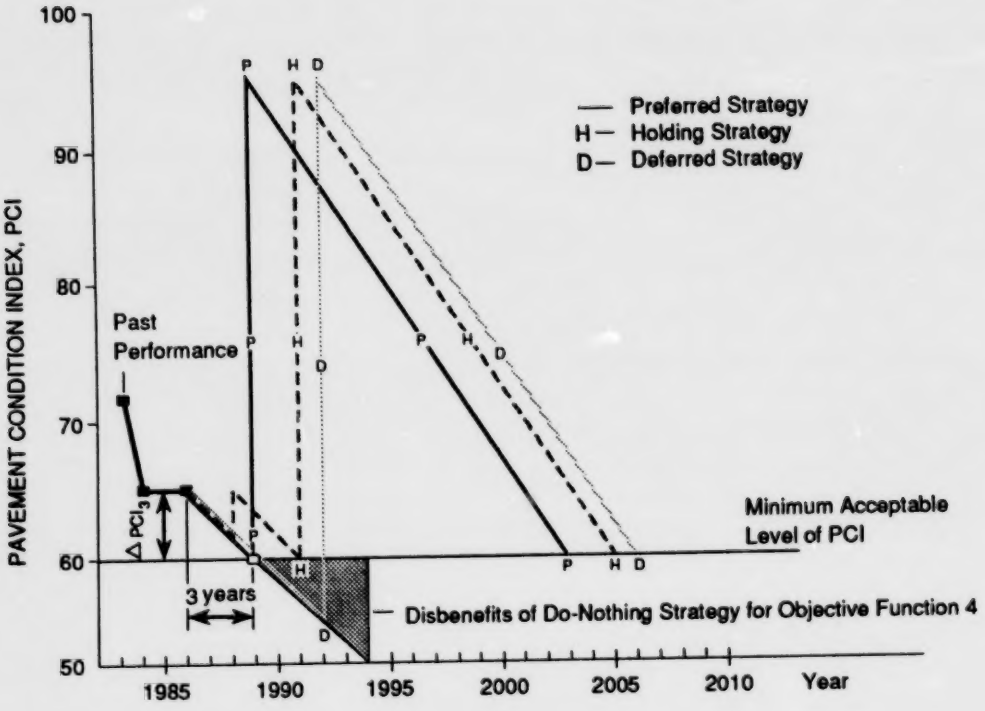


Figure 1/ Performance Curves for Section 22, Stratford District

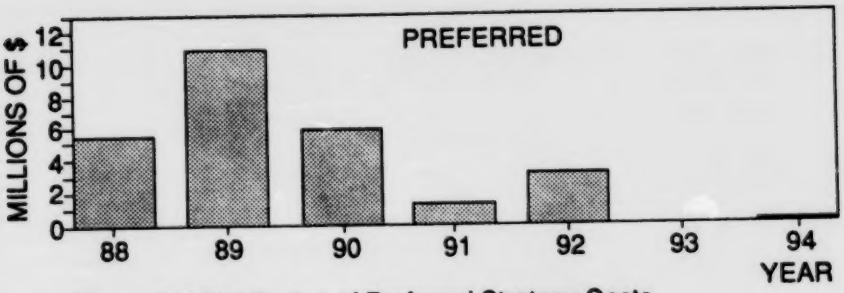


Figure 2a/ Distribution of Preferred Strategy Costs

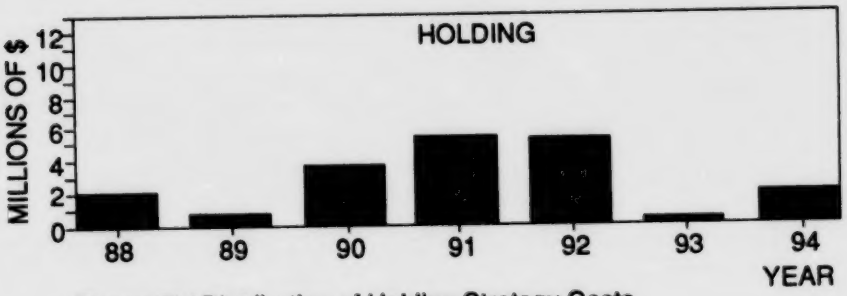


Figure 2b/ Distribution of Holding Strategy Costs

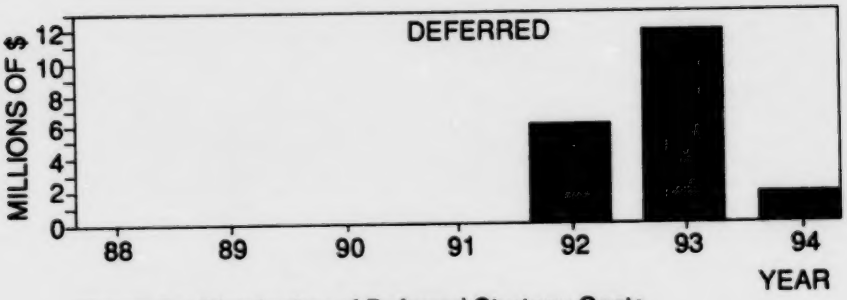


Figure 2c/ Distribution of Deferred Strategy Costs

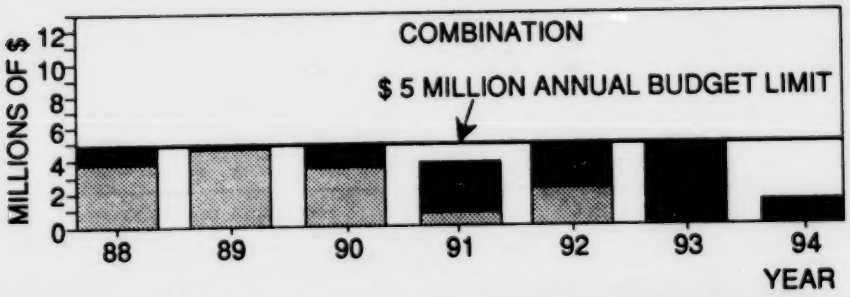


Figure 2d/ Distribution of Costs Obtained by Linear Programming

Figure 2/ Cost Composition for Linear Programming Solution, Objective Function 4, Stratford District

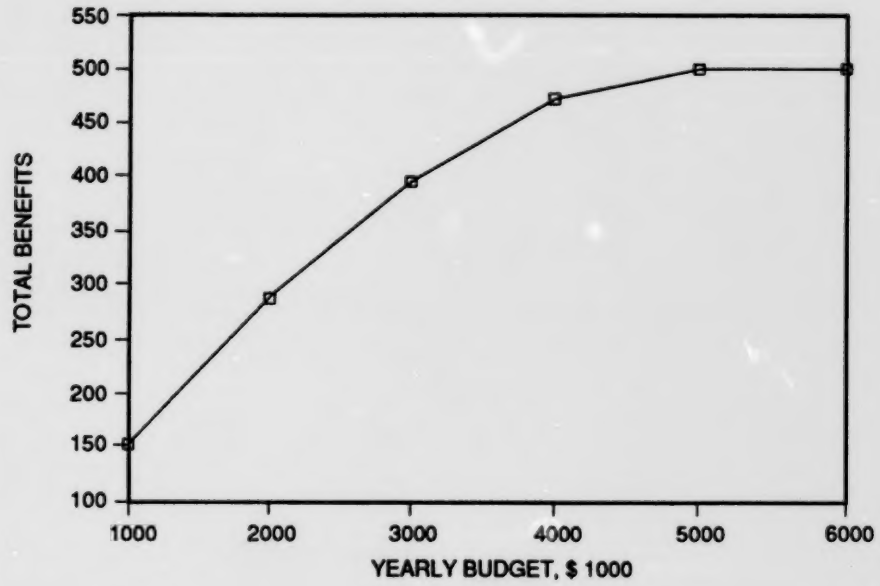


Figure 3/ Influence of Budget Constraints on the Investment Benefits

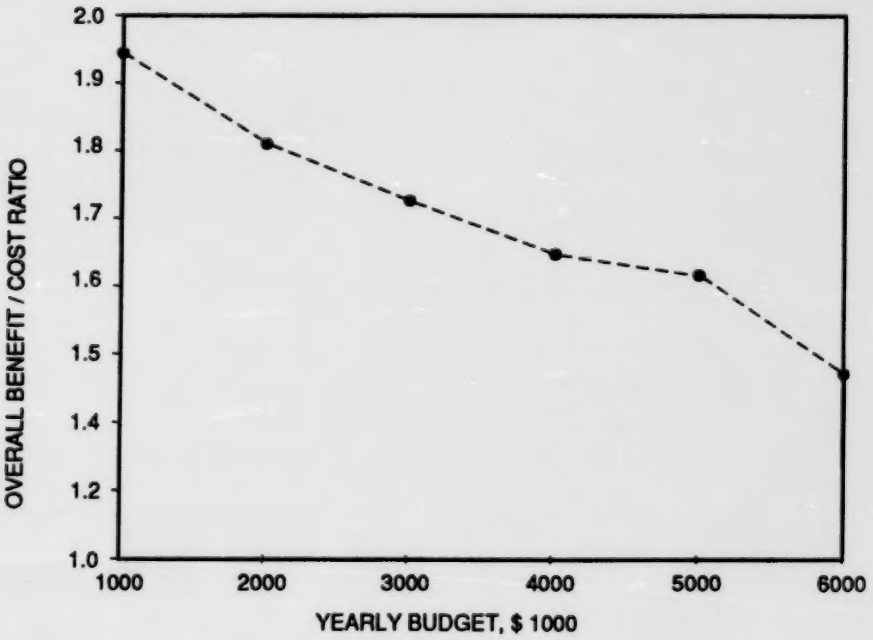


Figure 4/ Influence of Budget Constraints on the Overall Benefit/Cost Ratio